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APPLICATION OF CERAMICS BASED ON ALUMINUM OXIDE IN MEDICINE (A REVIEW)

E. S. Lukin,[1] S. V. Tarasova,[1] and A. V. Korolev[1]

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The application of pure aluminum oxide for medical purposes is analyzed. The main properties of corundum ceramics are described.

Medicine is one of the most promising and intensely growing application areas for ceramics. The use of ceramic materials significantly expands the possibilities of treating various diseases, in particular, orthopedic, dental, and maxillofacial problems [1, 2]. One of the global challenges of contemporary medical materials science is the development of artificial bone. The latter opens fundamentally new possibilities of using ceramics in substitutional and restorative surgery, neurosurgery, and stomatology [3].

Ceramic materials based on aluminum oxide are widely used in the manufacture of medical implants. The level of their properties is rather high, and yet it is far from the maximum possible level. The latest theoretical and technological solutions make it possible to perceptibly enhance the mechanical strength, chemical resistance, and other parameters of medical-purpose ceramics.

Regardless of the type of ceramics, the development of materials for medical purposes should take into account a number of fundamental requirements, which can be summarized as follows:

– capacity for multiple-year service under biologically unfavorable conditions;

– guaranty of mechanical stability and strength of ceramics, and maintaining a constant level of these properties for a long period;

– good adhesion to soft and hard body tissues ensuring reliable fixing of ceramic implants;

– sufficiently high chemical purity.

Medical ceramics can fulfill various functions: they are used to make bone prosthetic elements; ceramics are used as coating for metal implants; in dentistry, ceramics are used in metal ceramic dental prostheses, porcelain teeth, and filling mixtures [3 – 5].

[1] D. I. Mendeleev Russian Chemical Engineering University, Moscow, Russia.

Another application area is related to the development of medical instruments: disposable and long-service ceramic scalpels, which ensure good healing capacity, decrease blood loss, and ensure good antiseptic protection; ceramic filters and membranes for separation and purification of biological liquids; porous materials for intra-skin introduction of medication [3, 6].

For a long period, porcelain was virtually the only ceramic material used in medicine, since it has good cosmetological characteristics. However, the wear resistance and the physicomechanical parameters of porcelain prostheses in some cases do not meet the standard requirements; therefore, porcelain cannot be used in implants withstanding high mechanical loads. In such cases, ceramics based on aluminum oxide or corundum single crystals are successfully applied.

Leukosapphire single crystals and polycrystalline corundum materials are the most stable and inert oxide ceramics used in bone tissue substitution in orthopedics, in dental prostheses, and in maxillofacial surgery. Corundum ceramics have good biological characteristics for implantation of articulations. The latter is accomplished due to their high strength, low friction coefficient, and high wear resistance. Spheroid corundum articulations in combination with high-molecular polymer materials have several advantages over metal – polymer composites, including the absence of wear in the spheroid part of the joint, the absence of toxic impurities, which attend metals, and a decrease in the damage inflicted on connective tissues, due to the smaller size of polymer particles arising in wear [3].

Medical ceramics is usually divided into two main categories, depending on its interaction with the living body: bioinert materials exhibiting the minimum chemical, electrochemical, surface-catalytic, and other reactions with the body, and bioactive materials, which participate in the biochemical processes of the body [1]. It should be noted that

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TABLE 1

Bioactivity	Material				
	bone	titanium alloy	corundum ceramics	Cerabone (Japan)	KF
Connective tissue encapsulation	No	Yes	Yes	No	No
Toxicological body reactions	No	Possible	No	No	No
Probability of coalescence with bone	Yes	No	No	Yes (start of coalescence – 30 – 60 days)	Yes (end of coalescence – 90 days)

TABLE 2

Parameter	Material				
	bone	titanium alloy	corundum ceramics	Cerabone (Japan)	KF
Mean density, g/cm^3	–	4.5	3.9	–	2.8
Bending strength, MPa	90 – 170	390 – 440	490 – 590	160 – 180	Up to 150
Elasticity modulus, GPa	15 – 18	110 – 130	300 – 400	110 – 120	75
TCLE, 10^{-6} K^{-1}	–	9.9	6.0 – 8.0	–	9.5

the concept of bioactivity usually implies the probability of coalescence of the prosthetic material with the body, although this concept also includes the possibility of connective tissue encapsulation, toxic, and some other effects on the organism.

The data in Table 1 [3] indicate that corundum ceramics are regarded as bioinert materials with respect to their coalescence with body tissues. However, this type of ceramics has high mechanical strength, hardness, wear resistance, and chemical inertness. Due to the hydrophilic surface properties of aluminum oxide, a thin (below 5 nm) hydrated layer is formed on this surface, which adsorbs water and develops a protective film contributing to good biocompatibility. Furthermore, in the conditions of long-time existence in a living body, such ceramics retain their physical and biochemical properties, which fulfills the prerequisites for reaction-free implanting and lengthy service and makes these ceramics specially promising for use in dental and bone implants. Certain properties of corundum ceramics used in medicine, compared to other materials, are shown in Table 2 [3 – 5].

TABLE 3

Parameter	Class of material	
	A	B
Mean density, g/cm^3	At least 3.94	At least 3.90
Chemical composition, %:		
Al_2O_3	At least 99.5	
MgO	Not more than 0.3	
impurities ($R_2O + CaO + SiO_2$)	Not more than 0.1	
Mean crystal size, μm	Not more than 4.5	Not more than 7.0
Standard deviation, μm	Not more than 2.6	Not more than 3.5
Mean strength in four-point bending, MPa	At least 250	At least 150
Wear resistance (volume loss), mm^3	Not more than 0.01	Not standardized

One of the most important problems in the technology of medical-purpose ceramics based on aluminum oxide is the purity of the initial material. Furthermore, to obtain articles withstanding high service loads, it is necessary to have powders with precisely controlled properties, capable of sintering to zero open porosity without substantial recrystallization. The crystal size in the end material should not exceed 5 μm, the bending strength in three-point bending should be at least 500 MPa, and the critical coefficient of stress intensity at least 7 MPa · $m^{1/2}$. The process requires molding homogeneous intermediate products, so that the final article could be of the density close to the theoretical density. Only when all the above factors are taken into account, can the high requirements with respect to strength, hardness, and impact resistance, as well as the required surface purity after machine treatment, be satisfied.

The properties of bioactive and bioinert materials based on extra-purity aluminum oxide used as bone tissue substitutes should satisfy the requirements of the ISO 6474 international standard. This standard divides all materials based on aluminum oxide into two classes: A and B (Table 3). The class A materials are used for implants withstanding substantial loads (for instance, the carrying surface of a joint). The class B materials are intended for implants which are not subjected to great loads (for instance, stomatology).

It is established that oxide ceramics materials which do not contain modifying additives have low-level properties, hardly controllable microstructure, and low density [7, 8]. There are numerous known additives which have a positive effect on the sintering of corundum ceramics. However, the specified standard (Table 3) imposes additional requirements on the additives used in the production of medical ceramics.

Based on these requirements, as well as the preliminary research performed by us, it appears that only two types of modifying additives, namely, MgO and ZrO_2, are suitable for this application. It should be noted that the positive effect produced by these additives taken in an amount up to 0.5 wt.% has been long known in the technology of dense oxide ceramics [6 – 11].

Thus, corundum ceramics represent some of the most promising materials that can be successfully used in medicine. In order to obtain high-quality implants, it is essential to select appropriate firing conditions, which would ensure sintering to zero open porosity without perceptible recrystallization. The latter condition is related to the high requirement for mechanical strength and processability of ceramics imposed by the standard.

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